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# FIELD MEASUREMENTS OF SOIL RESISTIVITY

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Soil resistivity is a critical parameter in a grounding system design. This predesign resistivity data is usually obtained from field measurements. Two field measurement techniques are compared in order to validate them. The comparison is based on field tests at several sites and interpretation of the data using simple methods. The test results are useful in verifying the calculation of the grounding system performance at the test stations.

## 1.0 INTRODUCTION

The electrical resistivity of soil surrounding a grounding electrode is an important factor in designing grounding systems. The soil resistivity is normally obtained from field measurements and interpretation of this data. Resistivities vary horizontally, as well as vertically, and the data generally known as apparent resistivities (or conductivities) are obtained by conducting resistivity surveys at a subject site. Vertical variations are resolved by expanding the survey spacing. Horizontal variations are resolved using several locations on a site but these differences are usually not important. A soil model is then derived from the horizontally-averaged apparent resistivities using simple interpretation techniques or detailed computer methods.

The two soil resistivity measurement techniques being compared are the conventional Wenner four-probe method, which is the most widely used method, and the electromagnetic inductive technique. The latter method, although widely used in geoelectrical prospecting, is not commonly used by electrical utilities. However, the advantages of this method are presently being studied by several utilities for measuring soil resistivities. At Ontario Hydro, the Wenner method using a Megger DET2 instrument has normally been used by Research Division and Regional P&C while the Telecommunication Department of Design and Development - Transmission have recently acquired the electromagnetic inductive method using a Geonic's EM34 instrument. Both methods can measure the vertical variation of soil resistivity. In some instances, the test results using the latter technique have been found to yield lower resistivities than those using the former method. Therefore, it was decided to review the measurement techniques. Tests were conducted at Kleinburg TS, Hamilton Nebo TS, Saunders GS and St. Lawrence TS for this purpose. The project was requested and funded by Design and Development - Transmission.


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## 2.0 TEST PROCEDURE

Appendix A describes the two field measurement methods being compared. Soil resistivity surveys using both the Wenner and electromagnetic inductive methods were conducted together at the selected test locations in November, 1989. The test sites were chosen to cover a variety of soil resistivities. Also the soil resistivity data at Saunders GS was needed for design calculations. The geology at Kleinburg TS includes 10-20 m of overburden (loam and fine glacial till) with a shallow water table over shale. Hamilton Nebo TS site is characterized by shallow overburden (clay loam and well-drained clay) with limestone over shale. Here, the overburden at the station site was partially removed at the time of the test. At St. Lawrence TS, the overburden is also shallow and poorly drained with limestone below. At Saunders GS, the overburden over limestone may be thicker (0 - 10 m) than that at St. Lawrence TS and probably has low resistivities due to seepage of 30 - 60 Ω.m river water.

A Megger DET2 ground resistance tester was used by Research Division staff to take the Wenner readings at all sites. At Kleinburg TS, it was supplemented by a Gossen GEOM3 instrument which is sometimes used by Regional P&C staff. For each probe spacing, a second reading was taken with the test current injection reversed and the average value was used for the analysis. For each survey, the instrument was calibrated using a 100 Ω resistor and the required correction factors were applied to the instrument readings.

A Geonic's EM34 instrument was used by Telecommunications Department staff to take the conductivity readings in the electromagnetic surveys (hereafter called EM survey). At each survey location, measurements were performed in both horizontal and vertical dipole modes with intercoil spacings of 10 m, 20 m and 40 m. The instrument indicated negative readings in some cases possibly due to the interference from nearby power lines or other metallic objects in the vicinity. These negative readings were neglected and are not presented in this report.

## 3.0 INTERPRETATION OF TEST DATA

### 3.1 Data from Wenner Method

Apparent resistivities were calculated from the measured Wenner data using equation 7.1 of the Grounding Guide /1/. Varying measured resistivities with probe spacings indicate a multi-layer soil structure at the site. A two-layer soil model with an upper layer of resistivity $\rho_1$ of thickness d and a second layer of resistivity $\rho_2$ of infinite depth is often considered adequate for grounding system studies. Therefore, a two-layer soil model for each test location was interpreted from the measured Wenner data using the graphical method described in Appendix D of the Grounding Guide /1/. Here, the measured data points (apparent resistivity values) from each survey were plotted on a graph and then fitted to a two-layer model curve with scattered points eliminated. For station ground resistance calculations, the models were generally fitted to the data points at probe spacings of 5 m and beyond.

### 3.2 Data from Electromagnetic Inductive (EM) Method

The computer program PCLOOP developed by Geonics Ltd was used to analyze and interpret the EM survey data. This is a "forward" method requiring a trial and error fitting as explained in Appendix A. For the two-layer soil model derived from the Wenner surveys at each location, the program was used to calculate apparent conductivities for both horizontal and vertical dipole modes and intercoil spacings of 10 m, 20 m and 40 m. These calculated results were then compared with the measured values. The exercise was repeated by changing the model parameters until a best fit to the measured values was achieved. At some locations where more than two distinct layers were obvious from the measured

data, three layer models with a first layer of resistivity $\rho_1$ of thickness $d_1$, a second layer of resistivity $\rho_2$ of thickness $d_2$ and a bottom layer of resistivity $\rho_3$ of infinite depth, were also fitted.

## 4.0 INTERPRETED RESULTS FROM MEASUREMENTS

### 4.1 Kleinburg TS

The soil resistivity tests were conducted at Kleinburg TS on November 15, 1989. The weather on the test date was cold and raining, and the soil was wet.

#### a) Wenner Results

One Wenner survey was conducted south of the station and the resistance readings were obtained using both the Megger DET2 and Gossen GEOM3 instruments. The apparent resistivities calculated from the measured Wenner data are given in Table 1 along with modelled values.

The increasing and then decreasing measured resistivity with probe spacing clearly indicates a multi-layer soil structure at the site. The two-layer soil model (A) in Table 1 was approximately fitted to the increasing resistivity with any scattered points eliminated. The measured data at 100 m and 140 m probe spacings probably indicate a third deeper layer of lower resistivity but were neglected in the two-layer interpretation. Figure 1 plots the field data and the fitted two-layer model curve. Table 1 compares the modelled apparent resistivities with the measured results.

#### b) EM Results

One EM survey was conducted south of the station in the same location as the Wenner survey. The measured apparent conductivities from the EM survey are given in Table 2 and indicate a three-layer soil structure with a high resistive middle layer. Three-layer soil model (B) as indicated in Table 2 approximately fits the measured data. Alternately, a two-layer soil model (C) for comparison with the Wenner results was approximately fitted to the measured data at 10 m and 20 m coil spacings. The model parameters and the resulting apparent conductivities are given in Table 2.

TABLE 1

KLEINBURG TS - SOIL RESISTIVITY USING WENNER METHOD

| Probe Spacing (m) | Apparent Resistivities (Ω.m) Measured Using DET2 | Measured Using GEOM3 | Modelled (A) |
|---|---|---|---|
| 1 | 46.8 | 46.5 | 40 |
| 2 | 56.6 | 56.3 | 40 |
| 5 | 48.9 | 48.7 | 42 |
| 10 | 52.3 | 52.2 | 52 |
| 20 | 72.1 | 71.6 | 72 |
| 50 | 99.3 | 103.7 | 99 |
| 100 | 81.1 | 100.5 | 110 |
| 140 | 78.3 | 114.4 | 114 |

Fitted Two-Layer Model: (A) $\rho_1 = 40$ Ω.m, $d = 7.6$ m
$\rho_2 = 120$ Ω.m

TABLE 2

KLEINBURG TS - SOIL RESISTIVITY USING EM METHOD

| Coil Spacing (m) | Apparent Conductivities (mS/m) | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled (B) | Modelled (C) | Measured | Modelled (B) | Modelled (C) |
| 10 | 13.5 | 13.3 | 13.5 | 17.5 | 17.4 | 17.5 |
| 20 | 8.5 | 11.3 | 9.3 | 15.5 | 15.9 | 14.8 |
| 40 | 17 | 17.1 | 6.8 | 17.5 | 17.4 | 11.6 |

Fitted Three-Layer Model: (B) $\rho_1 = 40\ \Omega.m$, $d_1 = 7.7$ m, $\rho_2 = 170\ \Omega.m$, $d_2 = 30$ m $\rho_3 = 14\ \Omega.m$.

Fitted Two-Layer Model: (C) $\rho_1 = 40\ \Omega.m$, $d = 7.6$ m, $\rho_2 = 150\ \Omega.m$.

## 4.2 Hamilton Nebo TS

Soil resistivity surveys were conducted at Nebo TS on November 17, 1989. This is a new station under construction and the overburden was removed and/or levelled at the station site at the time of the surveys. Bedrock under 0 - 3 m thick clay was visible at the site. A gas pipe line runs along the south side of Hwy 53 approximately 50 m north of the station site. The weather on the test date was cold and the soil was wet due to previous rain.

### a) Wenner Results

Four Wenner resistivity surveys were conducted at Hamilton Nebo TS, surveys W1 and W2 south-east of the station site and surveys W3 and W4 at the station site. The survey locations are indicated in Figure 2. The apparent resistivities calculated from the measured Wenner data are given in Tables 3 and 4 along with modelled results.

The generally increasing resistivity with probe spacing indicates a multi-layer soil structure at the site. The decreased measured value at the probe spacing of 140 m from survey W1 (see Table 3) probably indicates a third layer of soil structure at the bottom and was neglected in a two-layer interpretation of the data. Separate two-layer soil models (A) and (B) as indicated in Table 3 were fitted to the measured data points from surveys W1 and W2, respectively. Figure 3 plots the field data and the fitted model curves for the test location. The measured results from surveys W3 and W4 at the station site vary only marginally and therefore, a two-layer soil model (C) for the site was approximately fitted to the data from both the surveys with scattered points eliminated. The modelled results are given in Table 4, along with the measured results and Figure 4 plots the field data and the corresponding fitted two-layer model curve.

## TABLE 3

## HAMILTON NEBO TS - SOIL RESISTIVITY USING WENNER METHOD
(Surveys South-East of Station Site)

| Probe Spacing (m) | Apparent Soil Resistivities (Ω.m) Survey W1 Measured | Survey W1 Modelled (A) | Survey W2 Measured | Survey W2 Modelled (B) |
|---|---|---|---|---|
| 1 | 29.5 | 35 | 29.9 | 46 |
| 2 | 43.0 | 43 | 57.4 | 56 |
| 5 | 80.1 | 80 | 111.8 | 110 |
| 10 | 157.7 | 158 | 210.5 | 210 |
| 20 | 329.2 | 330 | 461.2 | 400 |
| 50 | 732.0 | 700 | 791.7 | 900 |
| 100 | 780.4 | 1250 | 1388.6 | 1500 |
| 140 | 607.8 | 1600 | - | |

Fitted Two-Layer Models: (A) $\rho_1$ = 35 Ω.m, d = 3 m, $\rho_2$ = 3500 Ω.m

(B) $\rho_1$ = 45 Ω.m, d = 2.8 m, $\rho_2$ = 3150 Ω.m

## TABLE 4

## HAMILTON NEBO TS - SOIL RESISTIVITY USING WENNER METHOD
(Survey at Station Site)

| Probe Spacing (m) | Apparent Resistivities (Ω.m) Measured Survey W3 | Measured Survey W4 | Modelled (C) |
|---|---|---|---|
| 1 | 232.3 | 210.0 | 265 |
| 2 | 455.9 | 453.0 | 455 |
| 5 | 825.0 | 750.5 | 800 |
| 10 | 1058.1 | 1188.2 | 1080 |
| 20 | 1117.2 | - | 1200 |

Fitted Two-Layer Model: (C) $\rho_1$ = 100 Ω.m, d = 0.44 m
$\rho_2$ = 1300 Ω.m

b) **EM Results**

Two EM surveys E1 and E2 south-east of the station and one survey E3 at the station site were conducted at Hamilton Nebo TS. The survey locations are indicated in Figure 2 and the measured apparent conductivities are given in Tables 5 and 6, along with modelled results. Data measured in vertical dipole mode from surveys E1 and E2 were generally negative and therefore were discarded. The measured data in horizontal dipole mode from both the surveys indicate a three-layer soil structure with a high resistive middle layer. However, E2 survey yielded a considerably higher conductivity reading at 40 m coil spacing than that from the E1 survey and was not used in the interpretation. Therefore, a three-layer soil model (D) as indicated in Table 5 was approximately fitted to the data points from E1 survey. Also, separate two-layer soil models (E) and (F), as indicated in Table 5 were fitted to the measured data at 10 m and 20 m coil spacings from surveys E1 and E2, respectively, in order to compare with the Wenner model at the location. The fairly low resistivity (5Ω.m) of the third layer is probably due to the ill-conditioned measured results. Therefore, a three layer model (G) was derived based on the known geology at the site and the measured Wenner data at probe spacings of 50 m and beyond at the location. The modelled apparent conductivities are compared with the measured EM values in Table 5. The interpretation of the measured data from survey E3 at the station site was difficult due to the inconsistent data obtained in vertical and horizontal dipole modes. Here, three separate two-layer models were derived as indicated in Table 6; Model (H) with a low resistive bottom layer to fit the data in vertical dipole mode, Model (I) with a high resistive bottom layer to fit the data in horizontal dipole mode and Model (J) which is same as the Wenner model at the location. The model parameters and the resulting apparent conductivities are given in Tables 5 and 6, along with the measured values.

**TABLE 5**

**HAMILTON NEBO TS - SOIL RESISTIVITY USING EM METHOD**
(Surveys South-East of Station Site)

| Coil Spacing (m) | Apparent Conductivities (mS/m) Horizontal Dipole Mode | | | | | |
|---|---|---|---|---|---|---|
| | Survey E1 | | | | Survey E2 | |
| | Measured | Modelled | | | Measured | Modelled |
| | | (D) | (E) | (G) | | (F) |
| 10 | 11.5 | 11.3 | 11.7 | 12.1 | 9 | 8.7 |
| 20 | 7.5 | 8.1 | 7.3 | 7.9 | 5 | 5.4 |
| 40 | 10.0 | 10.2 | 4.1 | 5.1 | 50 | 3.1 |

Fitted Three-Layer Models: (D) $\rho_1 = 40$ Ω.m, $d_1 = 3.5$ m
$\rho_2 = 3500$ Ω.m, $d_2 = 52$ m, $\rho_3 = 5$ Ω.m

(G) $\rho_1 = 35$ Ω.m, $d_1 = 3$ m
$\rho_2 = 800$ Ω.m, $d_2 = 160$ m, $\rho_3 = 80$ Ω.m

Fitted Two-Layer Models: (E) $\rho_1 = 35$ Ω.m, $d = 3$ m, $\rho_2 = 3500$ Ω.m
(F) $\rho_1 = 45$ Ω.m, $d = 2.8$ m, $\rho_2 = 3500$ Ω.m

## TABLE 6

## HAMILTON NEBO TS - SOIL RESISTIVITY USING EM METHOD
(Survey at the Station Site)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | | Horizontal Dipole Mode | | | |
| | Measured | Modelled | | | Measured | Modelled | | |
| | | (H) | (I) | (J) | | (H) | (I) | (J) |
| 10 | 1.2 | 1.3 | 0.42 | 0.76 | 1.5 | 0.82 | 1.51 | 1.37 |
| 20 | 3.5 | 3.2 | 0.35 | 0.74 | 0.1 | 1.8 | 0.97 | 1.08 |
| 40 | - | 6.2 | 0.33 | 0.74 | - | 3.7 | 0.66 | 0.92 |

Fitted Two-Layer Models:
(H) $\rho_1$ = 3000 Ω.m, d = 25 m, $\rho_2$ = 75 Ω.m
(I) $\rho_1$ = 104 Ω.m, d = 0.75 m, $\rho_2$ = 3000 Ω.m
(J) $\rho_1$ = 100 Ω.m, d = 0.4 m, $\rho_2$ = 1300 Ω.m

### 4.3 Robert Moses GS (US Side)

Soil resistivity surveys were conducted at Robert Moses GS on November 22, 1989. The weather on the test date was cold and the ground was lightly covered with snow.

#### a) Wenner results

Two Wenner resistivity surveys W1 and W2 were conducted on low ground near the river and two surveys W3 and W4 were conducted on high ground near the TS at Robert Moses GS. The survey locations are indicated in Figure 5. The maximum probe spacing for some surveys was limited by accessibility. The apparent resistivities calculated from the measured Wenner data are given in Table 7, along with modelled results. A fifth survey conducted near the dam gave inconsistent readings and is not presented here. The generally increasing resistivity with probe spacing indicates a high resistivity bottom layer at the site. Two-layer soil models (A) and (B) were approximately fitted to the data at probe spacings of 5 m and beyond. The lower measured values at 140 m probe spacings are probably due to the proximity of metallic objects in the vicinity such as the station fence and were neglected in the interpretation. Figure 6 plots the field data and the fitted model curves. Table 7 compares the modelled apparent resistivities with the measured results.

## TABLE 7

## ROBERT MOSES GS - SOIL RESISTIVITY USING WENNER METHOD

| Probe Spacing (m) | Apparent Resistivities (Ω.m) Survey W1 Measured | Survey W2 Measured | Modelled (A) | Survey W3 Measured | Survey W4 Measured | Modelled (B) |
|---|---|---|---|---|---|---|
| 1 | 126.4 | 127.6 | 66 | 105.2 | 123.7 | 115 |
| 2 | 132.6 | 104.1 | 66 | 167.5 | 137.4 | 115 |
| 5 | 74.1 | 70.4 | 70 | 132.3 | 121.0 | 115 |
| 10 | 102.2 | 107.3 | 90 | 142.0 | 137.0 | 123 |
| 20 | 154.1 | - | 145 | 160.6 | 137.1 | 155 |
| 50 | 261.4 | - | 280 | 261.4 | - | 261 |
| 100 | 451.8 | - | 420 | 362.5 | - | 370 |
| 140 | 434.6 | - | 480 | 292.0 | - | 435 |

Fitted Two-Layer Models: (A) $\rho_1$ = 65 Ω.m, d = 10 m, $\rho_2$ = 650 Ω.m
(B) $\rho_1$ = 120 Ω.m, d = 20 m, $\rho_2$ = 600 Ω.m

b) EM Results

Three EM surveys (E1, E2 and E3) were conducted at the site as indicated in Figure 5 and the measured apparent conductivities are given in Tables 8, 9 and 10, respectively, along with modelled values. The decreasing conductivities with increasing coil spacings from survey E1 (Table 8) indicate a high resistvity bottom layer consistent with the Wenner results. Here, two-layer soil models (C) and (D) as indicated in Table 8 resulted in apparent conductivities which agree reasonably with the measured results. The E2 survey near the TS indicates an approximately uniform soil conductivity of 5.25 mS/m (resistivity of 190 Ω.m), neglecting the 10 m spacing in horizontal dipole mode. Two-layer and three-layer models (E) and (F) as indicated in Table 9 were also interpreted from the measured data and compared with the measured apparent resistivities in Table 9. The increasing conductivities with coil spacing from survey E3 near the dam indicate a low resistivity bottom layer and the fitted two-layer model (G) parameters are given in Table 10, along with the measured values.

## TABLE 8

## ROBERT MOSES GS - SOIL RESISTIVITY USING EM METHOD
(Survey Near River)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E1 | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled | | Measured | Modelled | |
| | | (C) | (D) | | (C) | (D) |
| 10 | 11.5 | 11.5 | 11.6 | 14 | 14.5 | 16.5 |
| 20 | 5.2 | 7.0 | 6.4 | 11.5 | 12.0 | 12.8 |
| 40 | 3.5 | 3.7 | 3.6 | 9 | 8.6 | 8.9 |

Fitted Two-Layer Models: (C) $\rho_1$ = 50 Ω.m, d = 10 m, $\rho_2$ = 500 Ω.m
(D) $\rho_1$ = 40 Ω.m, d = 7.2 m, $\rho_2$ = 400 Ω.m

## TABLE 9

## ROBERT MOSES GS - SOIL RESISTIVITY FROM EM METHOD
(Survey Near TS)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E2 | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled | | Measured | Modelled | |
| | | (E) | (F) | | (E) | (F) |
| 10 | 5.2 | 6.4 | 5.4 | 7.8 | 6.90 | 7.88 |
| 20 | 5.2 | 5.2 | 4.3 | 5.25 | 6.44 | 6.52 |
| 40 | 5 | 3.5 | 4.4 | 5.5 | 5.41 | 5.59 |

Fitted Two-Layer Model: (E) $\rho_1$ = 120 Ω.m, d = 20 m, $\rho_2$ = 600 Ω.m

Fitted Three-Layer Model: (F) $\rho_1$ = 78 Ω.m, $d_1$ = 5 m, $\rho_2$ = 1000 Ω.m, $d_2$ = 7 m
$\rho_3$ = 190 Ω.m

TABLE 10

ROBERT MOSES GS - SOIL RESISTIVITY FROM EM METHOD
(Survey Near Dam)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E3 | | | |
|---|---|---|---|---|
| | Vertical Dipole Mode | | Horizontal Dipole Mode | |
| | Measured | Modelled (G) | Measured | Modelled (G) |
| 10 | 14 | 15.1 | 10.5 | 10.5 |
| 20 | 20.5 | 18.9 | 16 | 15.4 |
| 40 | - | 20.2 | 18 | 19.3 |

Fitted Two-Layer Model: (G) $\rho_1 = 290\ \Omega.m$, $d = 4.5$ m, $\rho_2 = 35\ \Omega.m$

## 4.4 Saunders GS (Canadian Side)

Soil resistivity surveys were conducted at Saunders GS on November 23, 1989. The weather on the test date was cold and the ground was lightly covered with snow.

### a) Wenner Results

Three Wenner surveys (W5 near the river, W6 on high ground and W7 near the dam) were conducted at the site and the survey locations are indicated in Figure 5. The apparent soil resistivities calculated from the measured Wenner data are given in Table 11. Separate two-layer models (A), (B) and (C) as indicated in Table 11 were fitted approximately to the measured data from each survey. Figure 7 plots the field data and the fitted model curves. Table 11 compares the modelled apparent resistivities with the measured results. Two additional surveys conducted west of the HV tie lines near the river provided a limited number of data points and are not presented here. The data from both these surveys tend to yield a two-layer soil model similar to model (C) above from the survey W7.

### b) EM Results

Three EM surveys (E4, E5 and E6) as indicated in Figure 5 were conducted at Saunders GS and the measured apparent conductivities are given Tables 12, 13 and 14, respectively. The measured data in the horizontal dipole mode from survey E4 west of the HV tie lines near the river (Table 12) indicates a three-layer soil model at the location. Here, both three-layer and two-layer models (D) and (E) of Table 12 were fitted approximately to the measured data points. The decreasing conductivities with increasing coil spacings from surveys E5 east of the HV tie lines near the river (Table 13) indicate a high resistive bottom layer. Two separate two-layer models (F) and (G) were fitted approximately to the measured data points in vertical and horizontal dipole modes, respectively, and the modelled parameters are given in Table 13, along with the measured results. The interpretation of the measured data from survey E6 was difficult due to the inconsistent data obtained in vertical and horizontal dipole modes. Here, two separate two-layer models were derived as indicated in Table 14; Model (H) with a low resistive bottom layer to fit the data in vertical dipole mode and Model (I) with a high resistive bottom layer to fit the data in horizontal dipole mode. The modelled conductivities are given in Table 14, along with the measured results.

## TABLE 11

## SAUNDERS GS - SOIL RESISTIVITY USING WENNER METHOD

| Probe Spacing (m) | Apparent Resistivities (Ω.m) | | | | | |
|---|---|---|---|---|---|---|
| | Survey W5 | | Survey W6 | | Survey W7 | |
| | Measured | Modelled (A) | Measured | Modelled (B) | Measured | Modelled (C) |
| 1 | 352.6 | 84 | 71.7 | 84 | 59.6 | 33 |
| 2 | 353.5 | 84 | 77.9 | 84 | 43.6 | 33 |
| 5 | 202.3 | 88 | 85.1 | 84 | 36.9 | 34 |
| 10 | 135.1 | 100 | 89.6 | 90 | 41.9 | 42 |
| 20 | 145.9 | 146 | 111.6 | 122 | 67.1 | 67 |
| 50 | 300.0 | 300 | 240.7 | 240 | 129.4 | 129 |
| 100 | 451.8 | 452 | 395.8 | 395 | 161.5 | 175 |
| 140 | 531.3 | 540 | 493.5 | 493 | - | |

Fitted Two- Layer Models: (A) $\rho_1$ = 85 Ω.m, d = 14 m, $\rho_2$ = 850 Ω.m
(B) $\rho_1$ = 85 Ω.m, d = 18 m, $\rho_2$ = 850 Ω.m
(C) $\rho_1$ = 32 Ω.m, d = 10 m, $\rho_2$ = 256 Ω.m

## TABLE 12

## SAUNDERS GS - SOIL RESISTIVITY FROM EM METHOD
(Survey West of HV Lines Near River)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E4 | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled (D) | (E) | Measured | Modelled (D) | (E) |
| 10 | 12.5 | 16.1 | 13.2 | 14.5 | 14.5 | 14.6 |
| 20 | - | 13.0 | 10.5 | 17.5 | 15.0 | 13.6 |
| 40 | - | 6.1 | 7.0 | 11.5 | 12.2 | 11.3 |

Fitted Three-Layer Model: (D) $\rho_1$ = 75 Ω.m, $d_1$ = 9 m, $\rho_2$ = 4.5 Ω.m, $d_2$ = 1.2 m
$\rho_3$ = 3000 Ω.m

Fitted Two-Layer Model: (E) $\rho_1$ = 55 Ω.m, d = 18 m, $\rho_2$ = 260 Ω.m

TABLE 13

SAUNDERS GS - SOIL RESISTIVITY USING EM METHOD
(Survey East of HV Lines Near River)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E5 | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled | | Measured | Modelled | |
| | | (F) | (G) | | (F) | (G) |
| 10 | 11.5 | 11.4 | 7.5 | 8.1 | 13.4 | 8.2 |
| 20 | 7.6 | 7.6 | 6.2 | 7.7 | 11.6 | 7.7 |
| 40 | - | 4.0 | 4.7 | 7.3 | 8.6 | 6.7 |

Fitted Two-Layer Models: (F) $\rho_1$ = 57 Ω.m, d = 13.2 m, $\rho_2$ = 700 Ω.m
(G) $\rho_1$ = 100 Ω.m, d = 15 m, $\rho_2$ = 250 Ω.m

TABLE 14

SAUNDERS GS - SOIL RESISTIVITY USING EM METHOD
(Survey North of GS)

| Coil Spacing (m) | Apparent Conductivities (mS/m) - Survey E6 | | | | | |
|---|---|---|---|---|---|---|
| | Vertical Dipole Mode | | | Horizontal Dipole Mode | | |
| | Measured | Modelled | | Measured | Modelled | |
| | | (H) | (I) | | (H) | (I) |
| 10 | 6.8 | 6.7 | 3.0 | 3.8 | 6.4 | 3.8 |
| 20 | 7.3 | 7.4 | 2.1 | 3.2 | 7.1 | 3.2 |
| 40 | - | 8.0 | 1.5 | - | 7.8 | 2.5 |

Fitted Two-Layer Models: (H) $\rho_1$ = 145 Ω.m, d = 10.5 m, $\rho_2$ = 100 Ω.m
(I) $\rho_1$ = 190 Ω.m, d = 8 m, $\rho_2$ = 800 Ω.m

## 4.5 St. Lawrence TS

The soil resistivity tests were conducted west of St. Lawrence TS on November 23, 1989. The weather on the test date was cold and the ground was covered with light snow. The site was forested with standing water in some locations.

### a) Wenner Results

One Wenner survey W8 was conducted west of St Lawrence TS as indicated in Figure 5. The apparent resistivities calculated from the measured Wenner data are given in Table 15. The generally increasing resistivities with probe spacings were interpreted as a two-layer soil model (A) with scattered points eliminated. Figure 8 plots the field data and the fitted two-layer model curve. The modelled parameters are given in Table 15, along with the measured results.

TABLE 15

ST. LAWRENCE TS - SOIL RESISTIVITY USING WENNER METHOD

| Probe Spacing (m) | Apparent Resistivities (Ω.m) Measured | Modelled (A) |
|---|---|---|
| 1 | 103.5 | 150 |
| 2 | 156.7 | 150 |
| 5 | 191.6 | 150 |
| 10 | 177.2 | 180 |
| 20 | 257.6 | 260 |
| 50 | 283.1 | 420 |
| 100 | 510.2 | 520 |
| 140 | 577.9 | 570 |

Fitted Two-Layer Model: (A) $\rho_1$ = 150 .m, d = 11 m
$\rho_2$ = 600 Ω.m

b) EM Results

One EM survey E7 was conducted west of St. Lawrence TS as indicated in Figure 5 and the measured apparent conductivities are given in Table 16. The generally decreasing conductivities with increasing coil spacings indicate a two-layer soil model at the site with a high resistivity bottom layer. A two-layer soil model (B) as indicated in Table 16 resulted in apparent conductivities which agree reasonably with the measured values.

TABLE 16

ST. LAWRENCE TS - SOIL RESISTIVITY USING EM METHOD

| Coil Spacing (m) | Apparent Conductivities (mS/m) Vertical Dipole Mode | | Horizontal Dipole Mode | |
|---|---|---|---|---|
| | Measured | Modelled (B) | Measured | Modelled (B) |
| 10 | 4.4 | 4.3 | 4.2 | 4.6 |
| 20 | 3.7 | 3.5 | 4.9 | 4.3 |
| 40 | 3 | 2.5 | 3 | 3.7 |

Fitted Two-Layer Model: (B) $\rho_1$ = 180 Ω.m, d = 18 m, $\rho_2$ = 600 Ω.m

4.6 Resistivity of River Water

The three-pin method as explained in the Grounding Guide /1/ was used to measure the resistivity of river water. Here, a test rod of 8 mm radius was lowered into the river water in a canal (survey location #10 in Figure 5) with approximately 3 m spacing to the remote current and potential electrodes. Test current was circulated and the resistance reading was taken using the Megger DET2

instrument. Several resistance readings were taken by increasing the penetration depth of the test rod as given in Table 17. The resistivity of the water was calculated from the measured ground rod resistances using equation 3.4 of the Grounding Guide /1/ for driven rods and the results are given in Table 17.

TABLE 17

RESISTIVITY OF RIVER WATER

| Depth of Rod (m) | Measured Resistance (Ω) | Calculated Resistivity (Ω.m) |
|---|---|---|
| 0.0762 | 265 | 43 |
| 0.1524 | 165 | 43 |
| 0.3048 | 125 | 55 |
| 0.4572 | 87 | 52 |

## 5.0 DISCUSSION OF RESULTS

1. Both Wenner and EM surveys at Kleinburg TS indicate a three-layer soil structure at the site. A three-layer interpretation of the measured EM data indicates a very low, possibly questionable resistivity (14 Ω.m) in a third layer beyond a depth of 37.7 m. Neglecting this conductive third layer, the two-layer soil models interpreted from both the measured EM and Wenner data agree reasonably well and are consistent with the upper two layers of the three-layer soil model.

2. The correlation between the Megger DET2 and Gossen GEOM3 instruments used in the Wenner surveys is found to decrease at large probe spacings (Table 1) possibly due to the poor resolution of GEOM3 (0.01 Ω) compared to that of DET2 (0.001 Ω). The decreased Wenner resistivities at large probe spacings using the DET2 meter generally support the EM results at the location.

3. The EM surveys conducted south-east of Hamilton Nebo TS site (Table 5) indicate a three-layer soil structure at the location with a very low resistivity third layer at a great depth. The decreased apparent resistivity measured at 140 m probe spacing in the Wenner survey at this location (Table 3) may be due to a low resistivity third layer. However, the two EM surveys conducted at this location yield quite different readings, especially at 40 m coil spacing and therefore, the three-layer soil model interpreted from the measured EM data may not be good. Neglecting this conductive third layer at great depth, both the EM and Wenner data yield similar two-layer soil models consistent with the geology at the site. The generally negative readings in the vertical dipole mode (not used in the interpretation) and the inconsistent readings in the horizontal dipole mode from the EM surveys at this location may be due to the proximity of the HV lines. Also, the accuracy of the EM readings may be reduced in very high resistive soil.

4. Both the Wenner surveys conducted at the Hamilton Nebo TS site (Table 4) yield consistent resistivities at each probe spacing and indicate a two-layer soil structure at this location. Here, the limited maximum probe spacing may have resulted in a lower rock resistivity value than that from the Wenner surveys W1 and W2 south-east of the station site. The thin overburden interpreted from the measured data is consistent with the observed site condition. The EM surveys at this location gave inconsistent data in both vertical and horizontal dipole modes (Table 6). Furthermore, the EM results either from the vertical dipole mode or horizontal dipole mode do not agree with the Wenner results. The interference from the

nearby power lines and other metallic objects in the vicinity such as the gas pipe line may have affected the EM readings. Also, the dynamic range of the EM34 instrument is limited to 1 - 1000 Ω.m per the manufacturer's information /4/ and therefore, the EM readings may not be accurate in a soil of very high resistivity.

5. All four Wenner surveys at Robert Moses GS yield consistent resistivities at each probe spacing (Table 7). Here, both the Wenner and EM surveys resulted in two-layer soil models in reasonable agreement with the geology at the locations. Likewise, the results from the surveys near St. Lawrence TS using both the methods agree reasonably well. However, at Saunder's GS, the two measurement methods yield quite different results. The proximity of the many power lines in the area and other metallic objects in the vicinity such as underground cables and pipes may have affected the accuracy of the EM readings.

6. The two-layer interpretations of both EM and Wenner data at the GS area (both Canadian and US sides) generally yield lower resistivity values near the dam than those for the distant soil. The results indicate a rock resistivity of 260 Ω.m under the dam and 600 - 850 Ω.m away from the river. The low resistivity of the rock under the dam may be due to its saturation with river water.

7. In the Wenner surveys, interelectrode spacings of 100 m and over were generally required to identify a more conductive third layer of soil at the bottom than the upper layer. Conversely, the EM technique identifies such deep conductive layers at smaller intercoil spacings than the interelectrode spacings. Therefore, the EM technique may be better for exploring a deep conductive layer resting below an insulating layer.

8. A major problem when using the Wenner method for testing soil with high surface resistivity such as gravel and rock is driving sufficient test current into the earth. This problem is avoided in the EM method as test currents are magnetically induced in the earth.

9. The EM method might appear to be faster than the Wenner method since probe insertions, running long leads and large probe spacings for deep exploration depths are avoided in the EM method. However, the EM surveys were found to take almost the same time as the Wenner surveys due to the time involved in the setting-up, aligning coils and calibrating the intercoil spacing for each EM measurement. More experience with the EM instrument may increase the speed of EM surveys.

10. The graphical interpretation technique using curve fitting allows convenient two-layer interpretation of the Wenner data. Here, plotting helps give physical insight and makes bad data recognizable. More complex computer programs are generally needed to interpret a multi-layer (with more than two layers) soil model from the Wenner data. However, a two-layer soil model is often considered adequate for most grounding studies. Conversely, the EM data can be analyzed and interpreted as a multi-layer soil model (up to 10 layers) using the simple PC-based computer program PCLOOP. This is a "forward" method requiring trial and error. Even though the program is fast in calculating the apparent conductivities for a given multi-layer soil model, in some cases it was found difficult and time-consuming to get a soil model to fit the measured data. Also, filtering of bad data is difficult in the interpretation of EM data.

11. With three coil spacings and two coil orientations, six data points (apparent conductivities) are obtained for each EM survey. However, it was not generally possible to achieve good fitting to all the data. In some locations, the two-layer interpretation of the measured data in the vertical and horizontal dipole modes yielded inconsistent results. Conversely, the Wenner method was generally found to give consistent apparent resistivities at a given location.

12. Very small or negative readings and inconsistent data obtained using the EM technique at some survey locations are possibly due to interference from adjacent power lines and/or other metallic objects in the vicinity. Therefore, the EM method may not provide accurate results near operating stations and power lines. The vertical dipole mode was generally found more sensitive to the interference than the horizontal dipole mode.

13. The interelectrode spacing may be widely varied with the Wenner method to yield more information about the surface layering of the ground, the vertical sounding capability of the EM technique is limited by the three intercoil spacings of 10 m, 20 m and 40 m presently available with the instrumentation.

## 6.0 CONCLUSIONS

1. Soil resistivity tests using both Wenner and EM methods yield reasonably consistent results at locations free of interference from power lines and other metallic objects in the vicinity and where the resistivity is not too high.

2. Soil conductivity (resistivity) surveys using the EM method are marginally faster than the Wenner method, especially in exploring deep conductive layers and also for frozen soil and in forests.

3. Since the EM method magnetically induces test currents in the earth, problems associated with the Wenner method in high resistive surface soil such as gravel and rock are not encountered in the EM method.

4. Test results indicate that the EM technique offers a deeper exploration capability at smaller intercoil spacings than the interelectrode spacings in the Wenner method especially in cases where the bottom layer of the soil is more conductive than the upper layer. Therefore, the EM technique is more applicable than the Wenner method at locations where horizontal accessibility is limited.

5. The Wenner method yields more information about the surface layering since more interelectrode spacings are available.

6. A major limitation in the use of the EM method is its susceptibility to interference from nearby power lines and other metallic objects in the vicinity such as underground cables and pipes. The EM data were generally found negative or inconsistent in such cases. The Wenner method was not affected very much by such interferences.

7. The graphical interpretation technique using curve fitting of Wenner data helps give physical insight and make bad data more recognizable than the interpretation technique of EM data using the computer program PCLOOP.

8. Soil resistivity measurements using the Wenner and EM methods yielded the following two-layer soil models at the different test locations. The results are generally consistent with the geology at the sites. The resistivity of St. Lawrence river water was measured as approximately 50 Ω.m.

| Test Site | $\rho_1$ (Ω.m) | d (m) | $\rho_2$ (Ω.m) |
|---|---|---|---|
| Kleinburg TS | 40 | 7.6 | 120 - 150 |
| Hamilton Nebo TS | | | |
| a) Station Site | 100 | 0.4 | 1300 |
| b) South-East of TS | 35 - 45 | 3 | 3150 - 3500 |
| Saunders GS (Both Canada and US) | | | |
| a) Near Dam | 32 - 55 | 10 - 18 | 260 |
| b) Near River | 50 - 85 | 10 - 14 | 500 - 850 |
| c) On High Ground | 85 - 120 | 18 - 20 | 600 - 850 |
| St. Lawrence TS | 150 - 180 | 11 - 18 | 600 - 850 |

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RPP:am

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3. IEEE Standard 81, IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potential of a Ground System, 1983 Edition.

4. J.D. McNeill, "Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers," Geonics Ltd Technical Note TN-6, dated October, 1980.

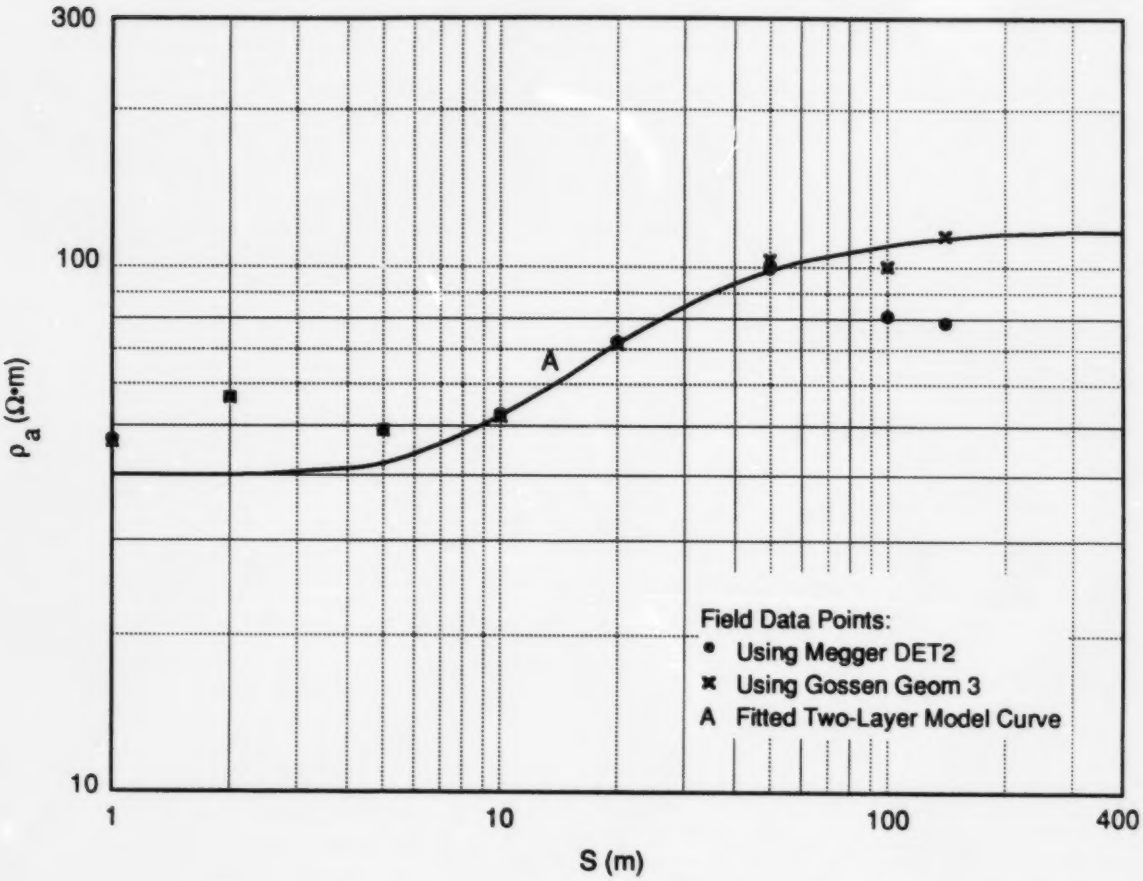


**FIGURE 1**

**KLEINBURG TS - WENNER SURVEY**
**APPARENT SOIL RESISTIVITY MODEL**

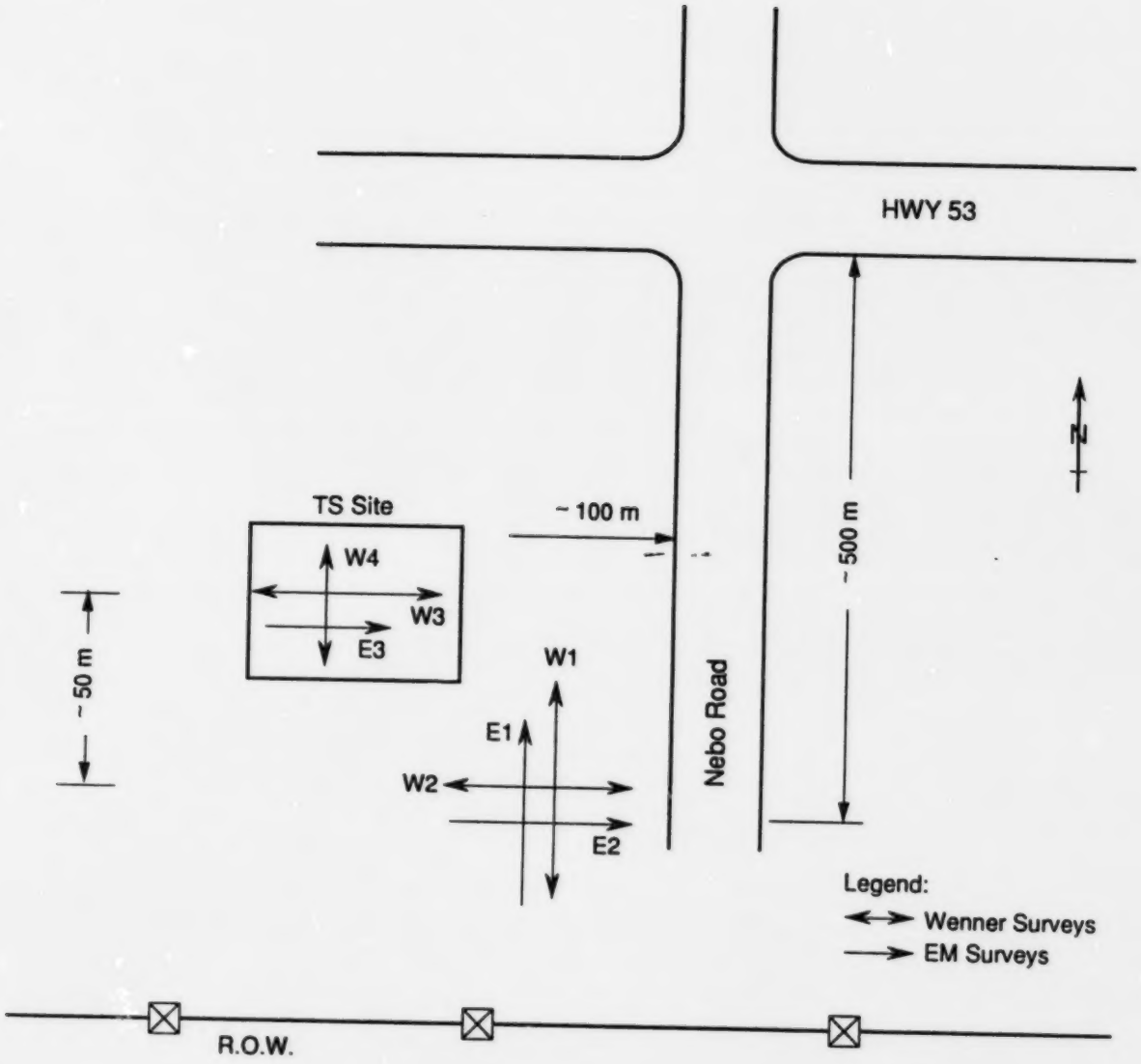


**FIGURE 2**

**HAMILTON NEBO TS LAYOUT WITH RESPECT TO SOIL RESISTIVITY SURVEYS**

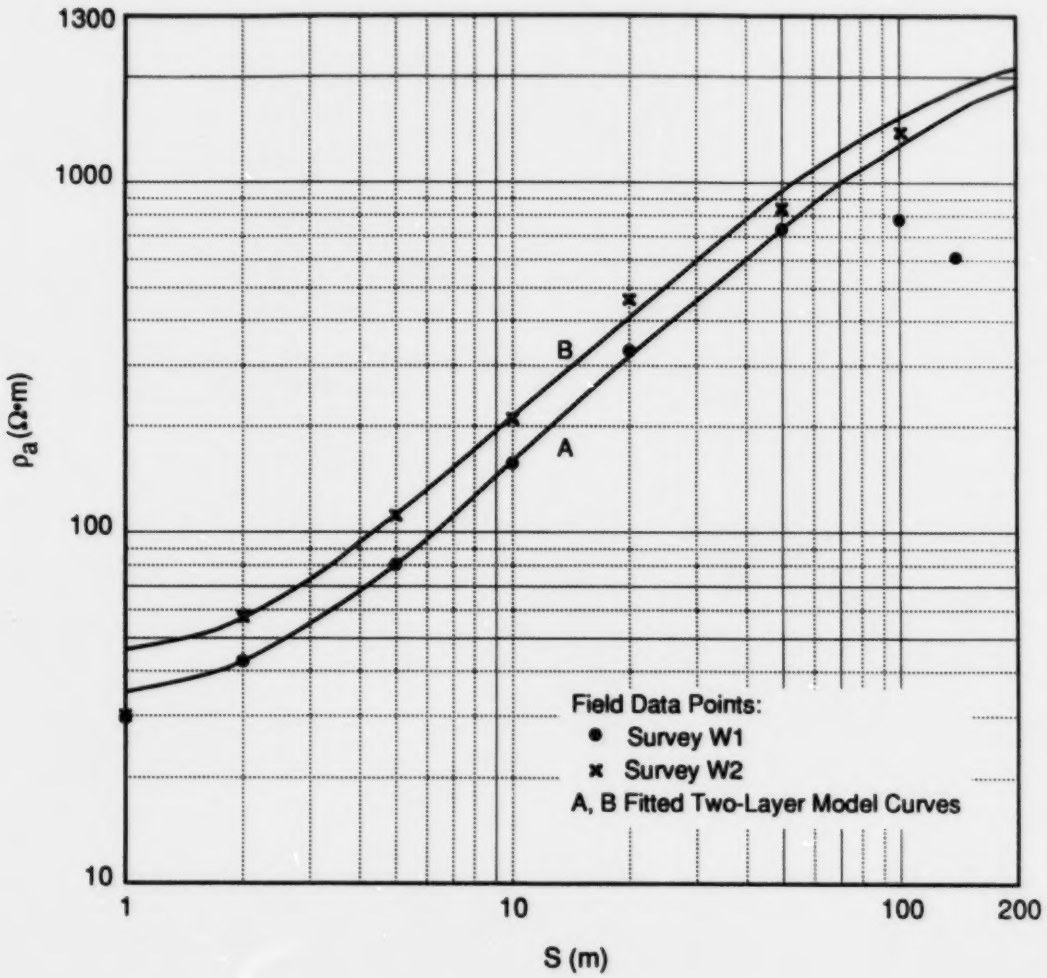


**FIGURE 3**

**HAMILTON NEBO TS - WENNER SURVEYS W1 & W2**
**APPARENT SOIL RESISTIVITY MODEL**

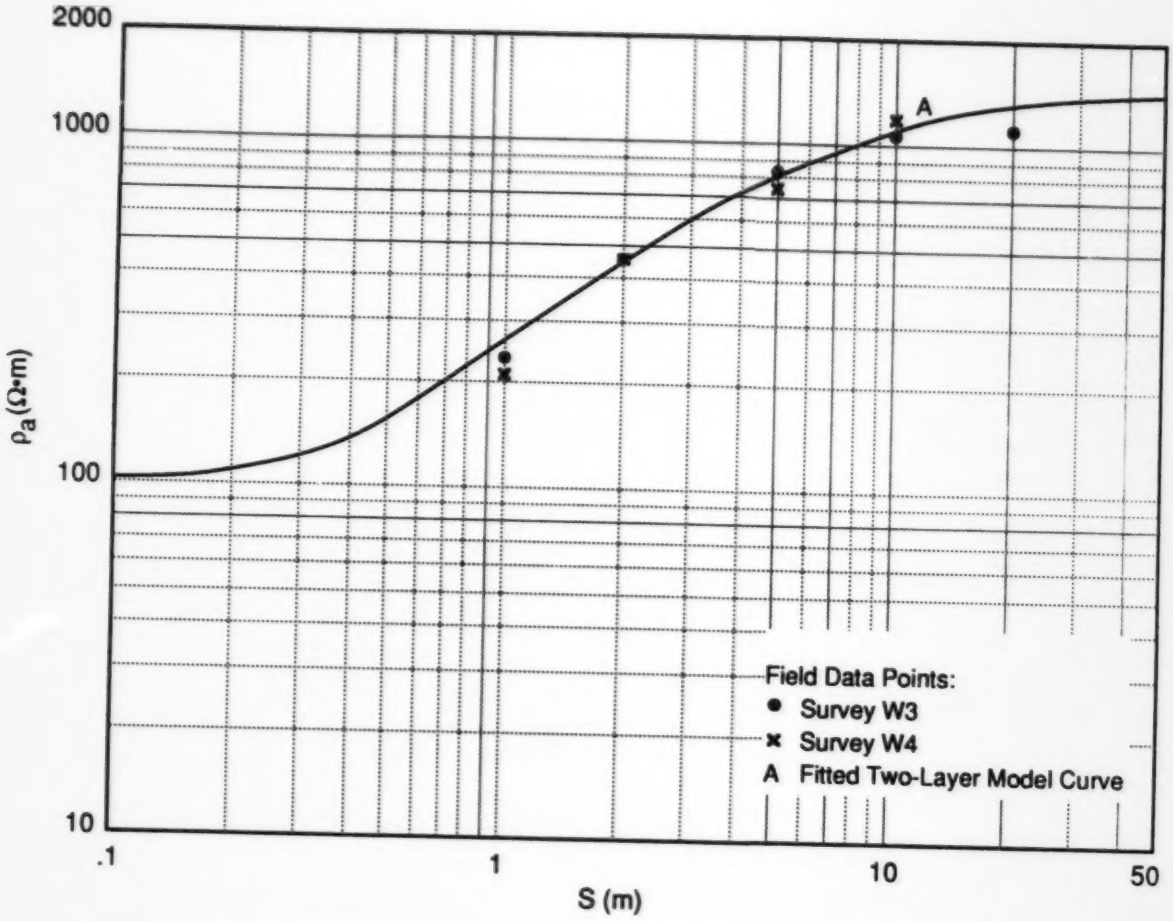


**FIGURE 4**

**HAMILTON NEBO TS - WENNER SURVEYS W3 & W4**
**APPARENT SOIL RESISTIVITY MODEL**

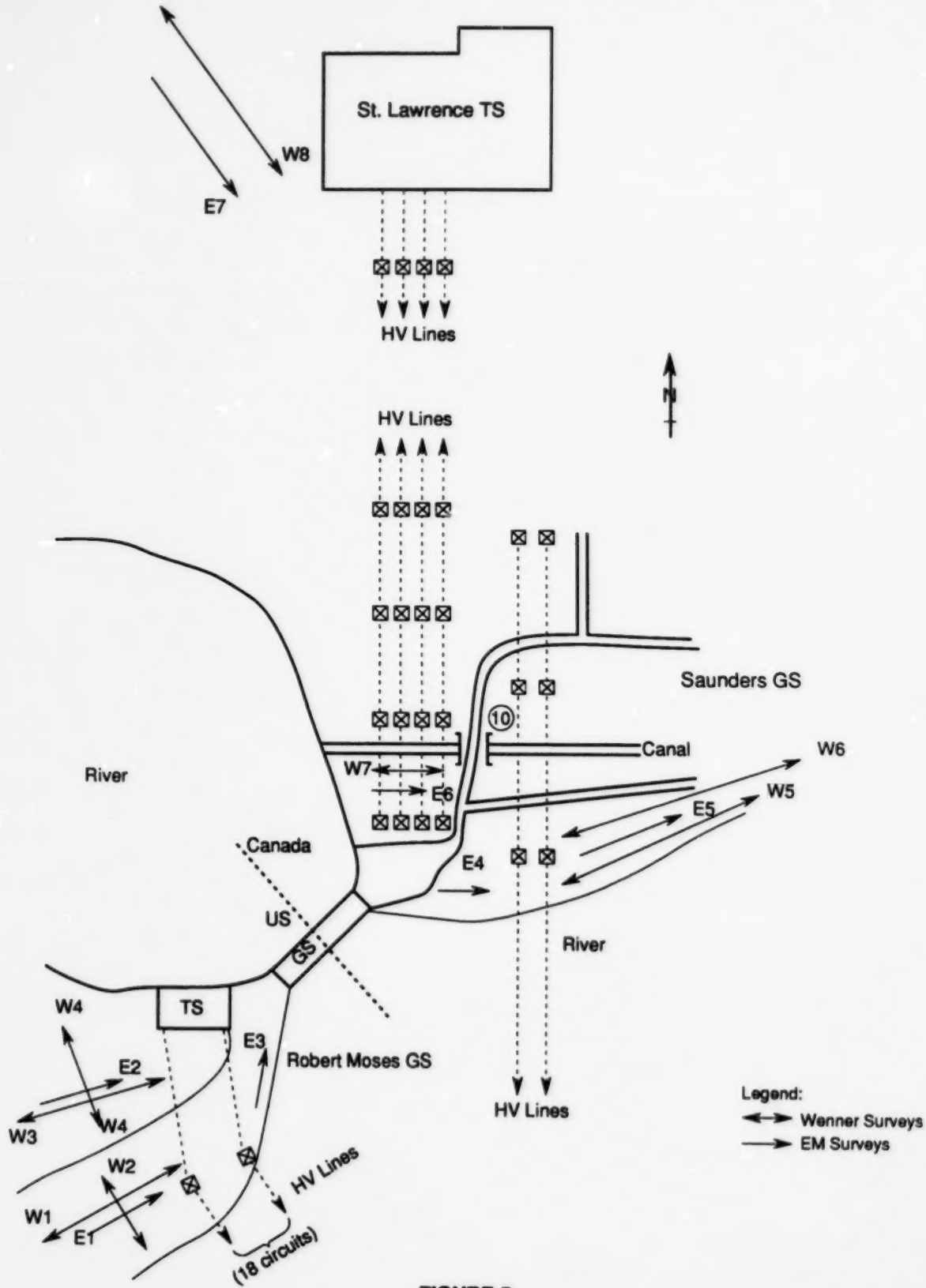


**FIGURE 5**

**SAUNDERS GS AREA LAYOUT WITH RESPECT TO SOIL RESISTIVITY SURVEYS**



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90-148

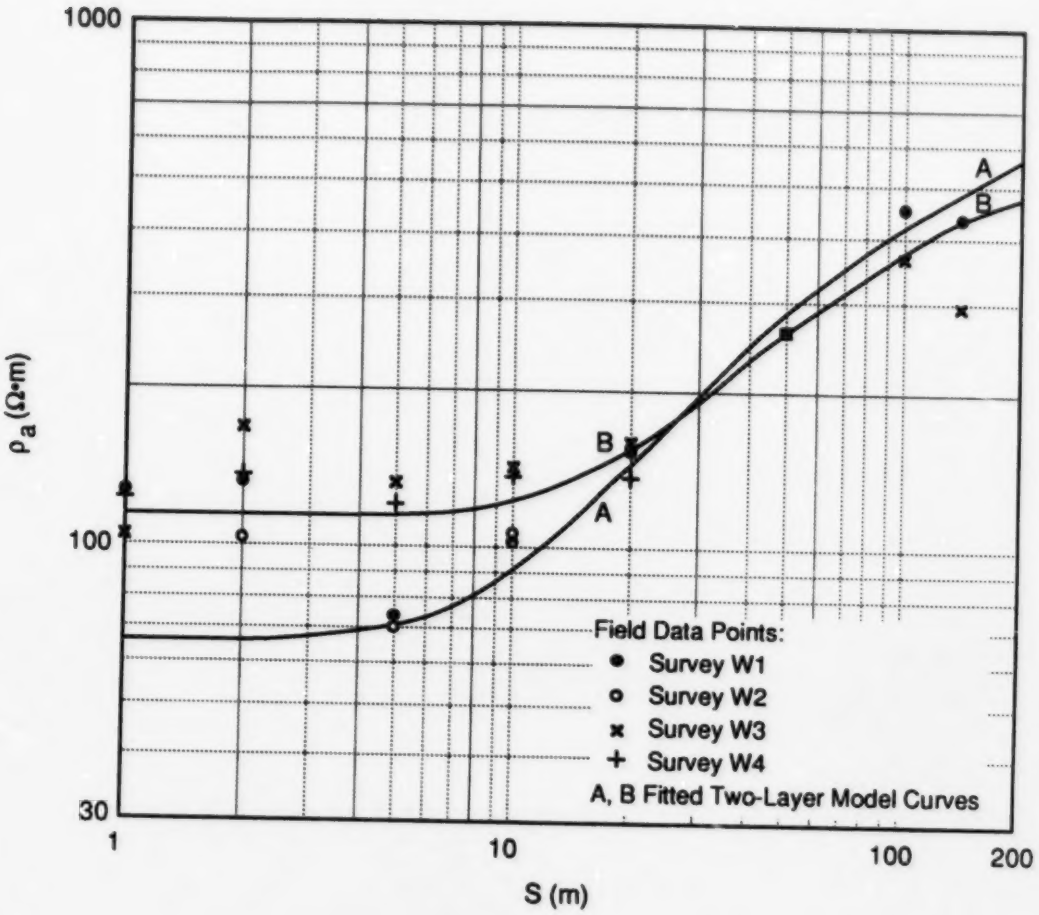


**FIGURE 6**

**ROBERT MOSES TS - WENNER SURVEYS**
**APPARENT SOIL RESISTIVITY MODELS**

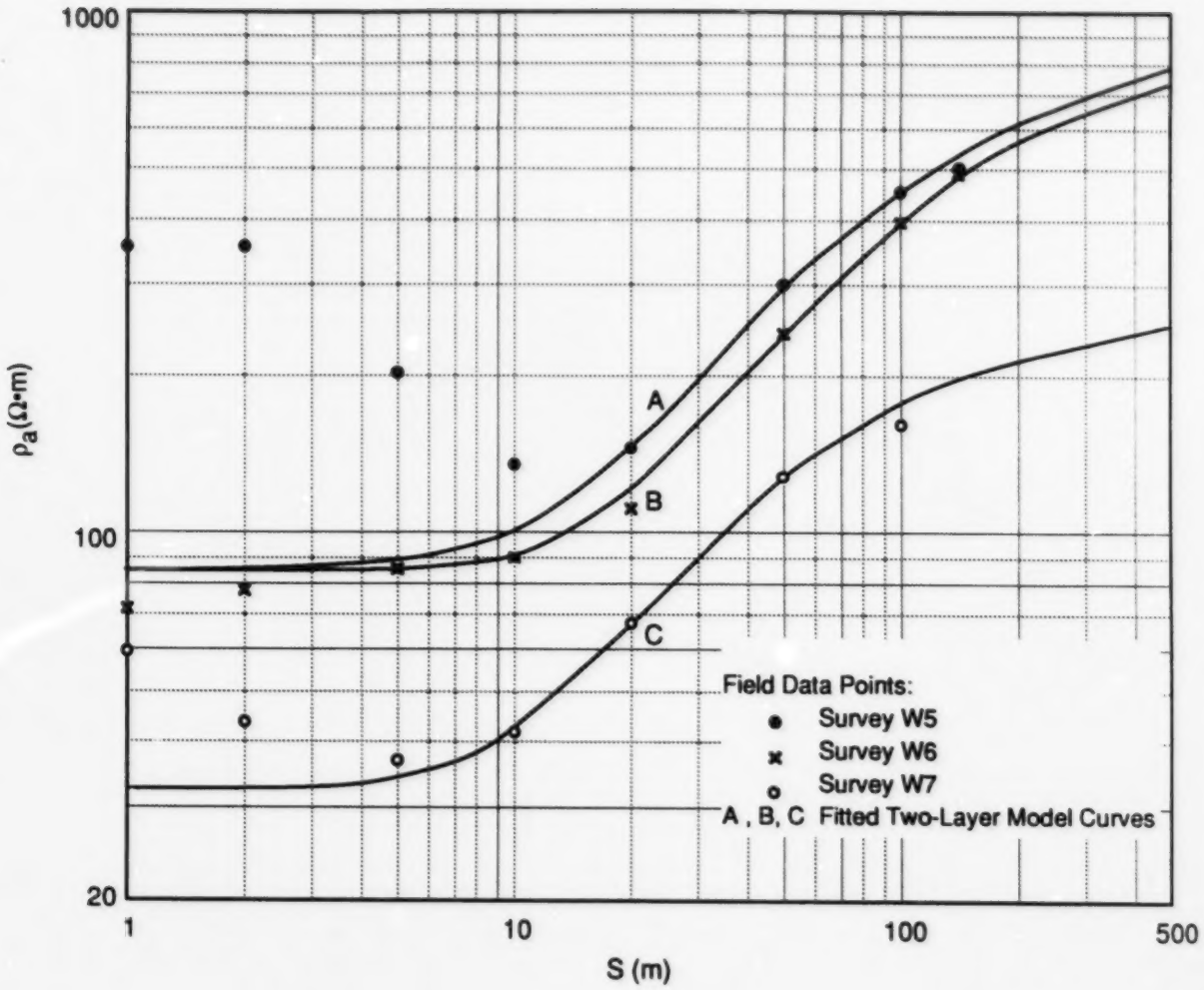


**FIGURE 7**

**SAUNDERS GS - WENNER SURVEYS**
**APPARENT SOIL RESISTIVITY MODEL**

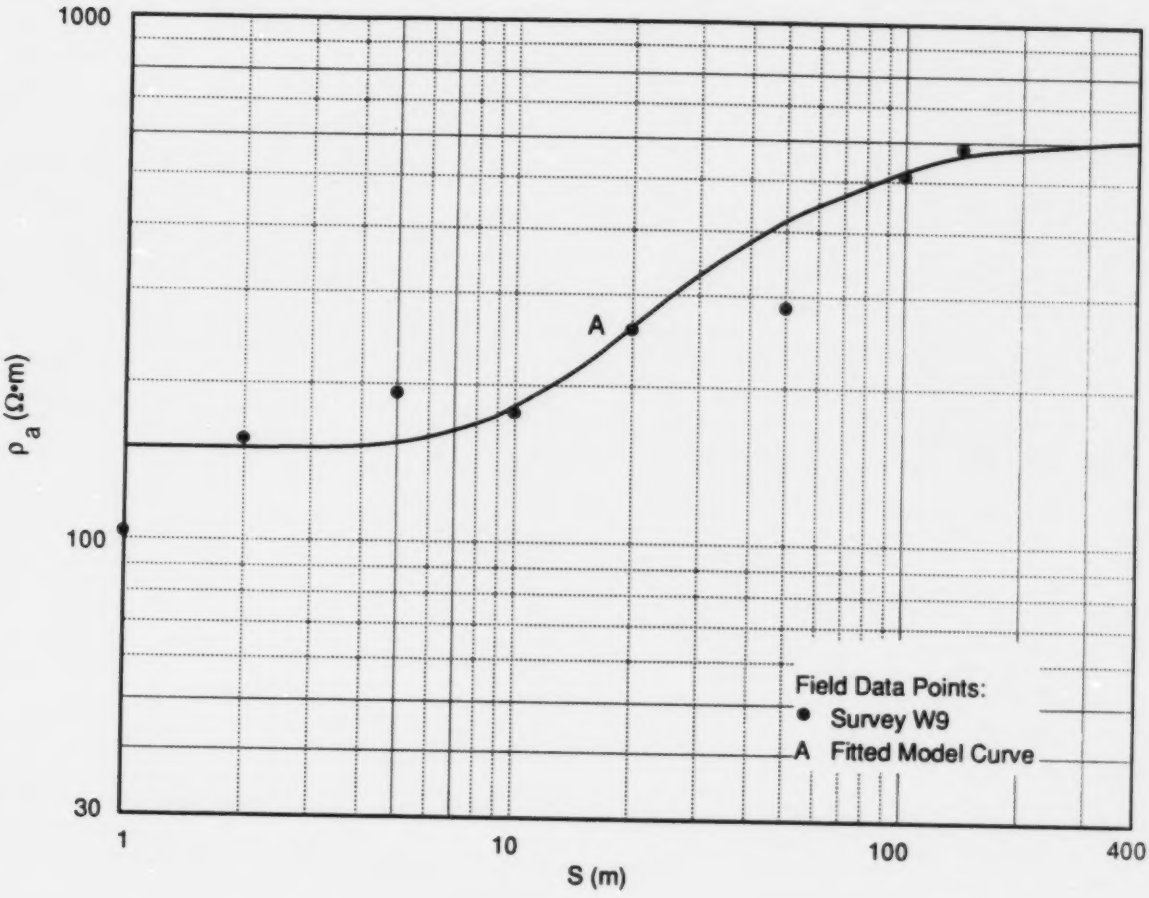


**FIGURE 8**

**ST. LAWRENCE TS - WENNER SURVEY**
**APPARENT SOIL RESISTIVITY MODEL**

## APPENDIX A

## SOIL RESISTIVITY MEASUREMENT TECHNIQUES

### 1. Wenner Four-Probe Method

The Wenner four-probe method is the most widely used technique in practice for measuring soil resistivities. Here, four small electrodes are driven into the soil to a depth d and spaced at equal intervals S along a straight line. A test current is passed between the two outer electrodes and the current and the potential between the two inner electrodes are measured using a suitable ground resistance tester to give the resistance value. Several commercial instruments are available for the purpose. If the electrode depth is kept small compared to the distance between them, then the apparent soil resistivity,

$$\rho_a(S) = 2 \pi S R_m \quad \Omega.m \qquad (1)$$

where, S is the distance between the electrodes in meters and $R_m$ is the resistance reading of the instrument in ohms.

As the effective depth of exploration depends on the electrode spacing, a vertical variation in the soil resistivity is obtained by expanding the electrode spacing. At a selected test location, a set of data with increasing values of S are obtained and the corresponding apparent resistivities are calculated using the above formula. If the apparent resistivities vary little with respect to the distances, such a soil can be interpreted as having a uniform soil. Varying resistivities with probe spacings indicate a multi-layer soil structure. When two or more distinct layers of soil may appear in the measured apparent resistivity profile, representation of the multi-layer soil by an equivalent two-layer model is often considered adequate for designing a safe grounding system. In such cases, the measured apparent resistivities from the Wenner survey are interpreted as a two-layer soil model using the graphical method explained in Appendix D of the Grounding Guide /1/ or other available computer programs. Any unwanted data can be ignored in the interpretation. Details regarding the measurements and interpretation of the data are given in the Grounding Guide /1/, IEEE Guide-80 /2/ and IEEE Guide 81 /3/. The Wenner array method has been used by Research Division in grounding studies and by Regional P&C.

### 2. Electromagnetic Inductive Method

A transmitter coil energized with an alternating current at three audio frequencies depending on spacing, is placed on the earth's surface. The time-varying magnetic field arising from the transmitter coil electromagnetically induces small currents in the earth with an amplitude linearly proportional to the terrain conductivity. These currents generate a secondary magnetic field in the earth which is sensed together with the primary field by a receiver coil spaced 10 m, 20 m or 40 m from the transmitter coil. The effective penetration depth of the magnetic field depends on the distance between the two coils and the varying frequency. The apparent terrain conductivity which is proportional to the ratio of the secondary to the primary magnetic field is detected and directly displayed. The coils can be placed either in their vertical planes (horizontal dipole mode) or horizontal planes (vertical dipole mode) having different sensitivity to various depths. The approximate exploration depths for both horizontal and vertical dipole modes are given in Table A1.

TABLE A1

APPROXIMATE EXPLORATION DEPTHS FOR EM34 INSTRUMENT AT VARIOUS INTERCOIL SPACINGS

| Intercoil Spacing(m) | Exploration Depth (m) | |
|---|---|---|
| | Horizontal Dipole | Vertical Dipole |
| 10 | 7.5 | 15 |
| 20 | 15 | 30 |
| 40 | 30 | 60 |

The electromagnetic inductive method, even though widely used in geoelectrical prospecting, has not been commonly used by electrical utilities. Geonics Limited, a leading company in electromagnetics, has developed instrumentation employing this method to measure terrain conductivity /4/. The instrument permits direct read-out of the apparent conductivity in ms/m.

At a selected location, two sets of conductivity readings with the three intercoil spacings (10, 20 and 40 meters) are obtained in horizontal and vertical dipole modes. When the measured conductivities are found to vary with depth, the data is analyzed and interpreted as a multi-layer soil model using the computer program PCLOOP which is developed by Geonics Limited. This is a forward method using trial and error. The program requires an IBM PC or equivalent with 160 K RAM memory and 8087 numeric coprocessor, operating under DOS 2.0 or later version. For a given multi-layer (up to 10 layers) soil model, the program calculates apparent conductivities and resistivities at the three coil spacings in both horizontal and vertical modes. The calculated apparent conductivities are then compared with the measured values and the exercise is repeated until a satisfactory fit is achieved.